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EMSA

# Intra-strand resistance and current transfer length in multi-filamentary NbTi, $Nb_3Sn$, $MgB_2$, BSSCO and ReBCO conductors

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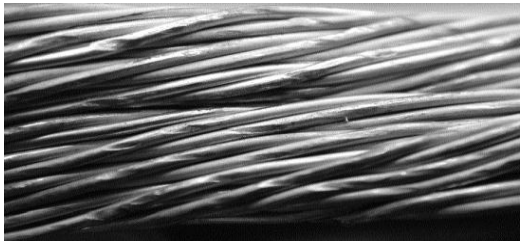
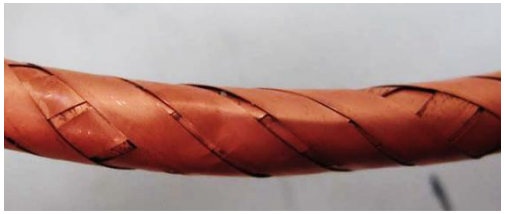
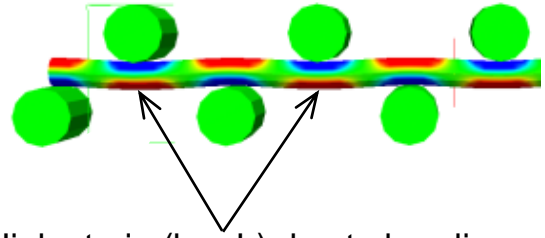
# Motivation

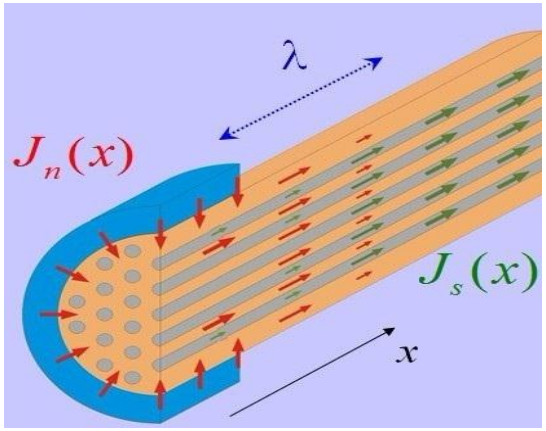
- Aim: (extensive) database for intra-strand/tape resistances of multi-filamentary NbTi, $Nb_3Sn$, $MgB_2$, BSSCO and ReBCO superconductors
- To quantify the impact of locally varying strain conditions, filament fracture and current (re-)distribution process between matrix and superconducting filaments occurring at current injection points in relation to strand internal architecture
- Modeling transport properties of strain sensitive $Nb_3Sn$ strand under load and scaling to full size CICCs subjected to large EM forces





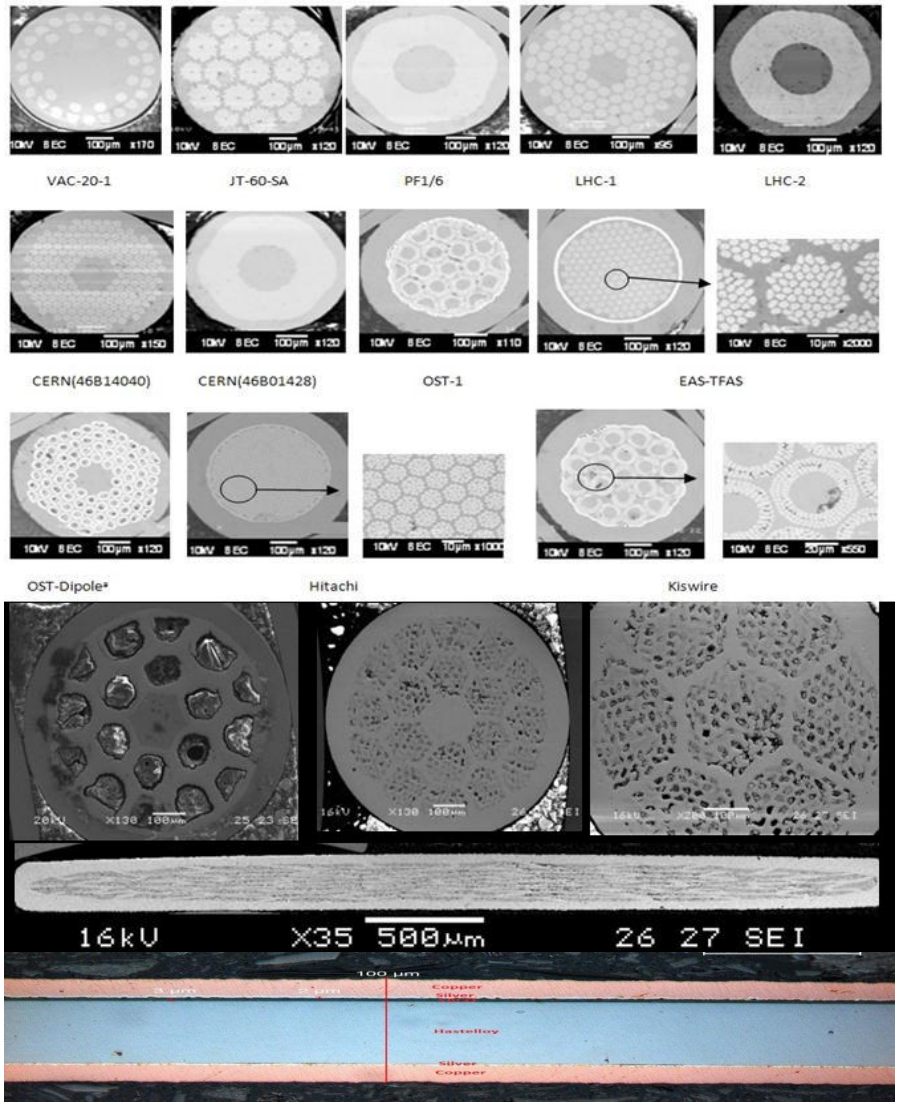


High strain (low $I_c$) due to bending
➔ Current transfer among filaments (cracks & strain variations)




Current transfer length

# Intra Strand Resistance characteristics



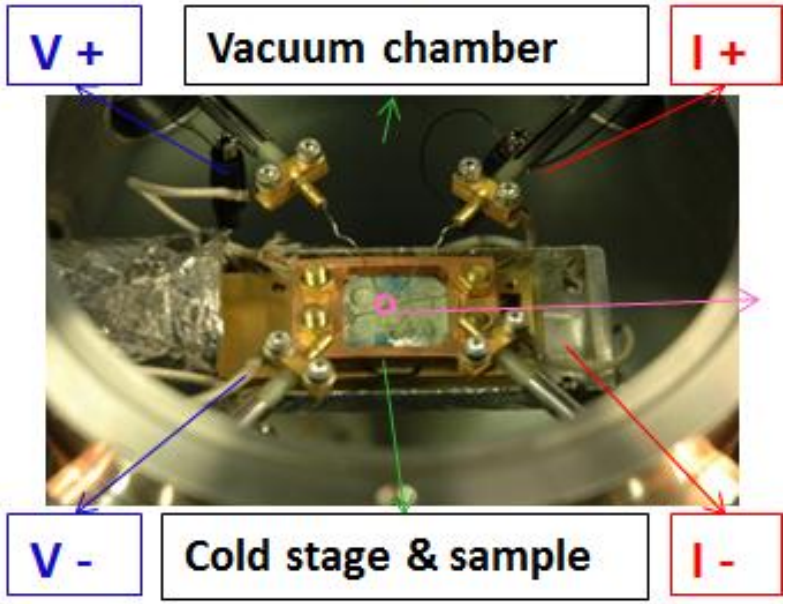

Superconducting wires/tapes: NbTi, $Nb_3Sn$, $MgB_2$, Bi2212, Bi2223 and ReBCO

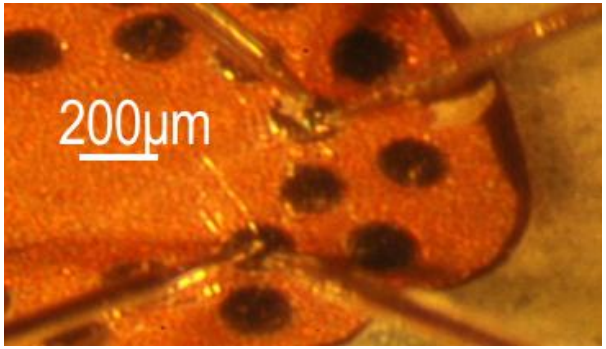
Number of filaments: from 1 – 14,040

Diameter of filaments: from 2.6 - 160 µm

Matrix: Cu, bronze, Ag, Nb

# Experimental setup: intra-strand resistance

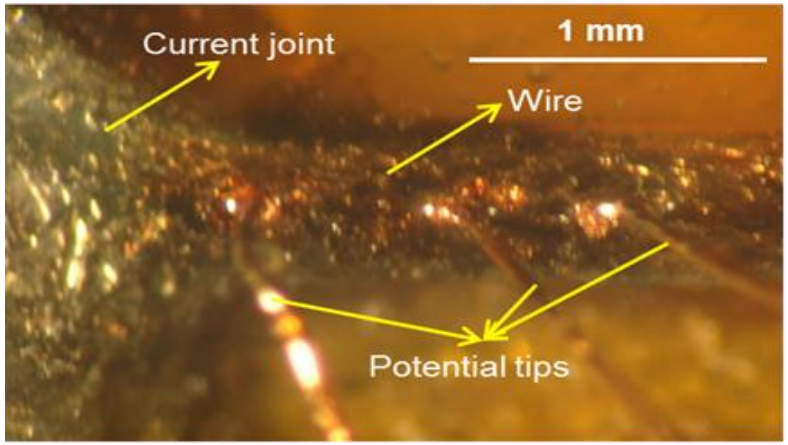


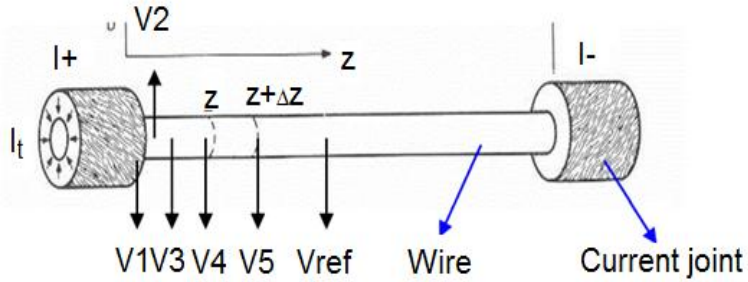




- Direct measurement of inter-filament resistance and overall potential distribution across the transverse cross-section of thin strand 'slices' (double polishing).
- 4 micro-needles are positioned anywhere in the cross section, serving as voltage taps and current leads for 4-point *V-I* measurements.

C Zhou, Y Miyoshi, E P A van Lanen, M Dhalle and A Nijhuis, Supercond. Sci. Technol. 25 015013 (2012)

# Experimental setup: current transfer length




- Current transfer length is determined by the matrix-to-filament resistance, matrix resistance, and geometry of cross-section.
- Copper potential tips (diameter of 50 μm) on the sample by spot-welding to monitor the potential distribution along the sample length.
- The current is injected and distributed equally at the outer shell.

# Model: intra-wire resistance

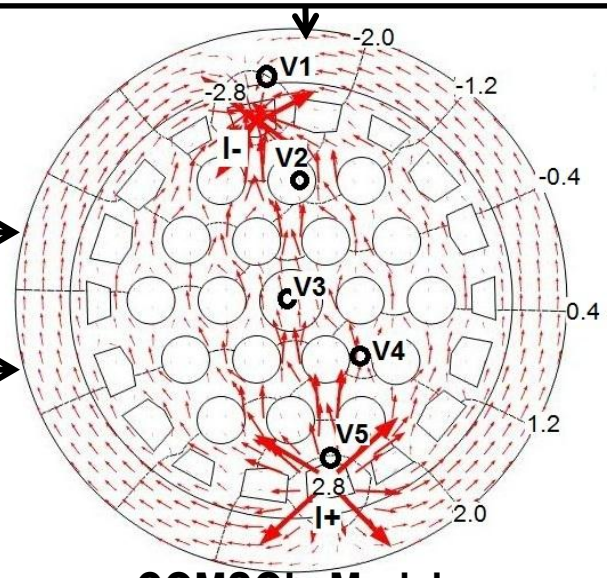
Filament-to-matrix contact resistivity

**Unknown parameter to be solved**

matrix resistivity *(RRR,EDX for bronze)*

cross-sectional layout (*Microscopy*)

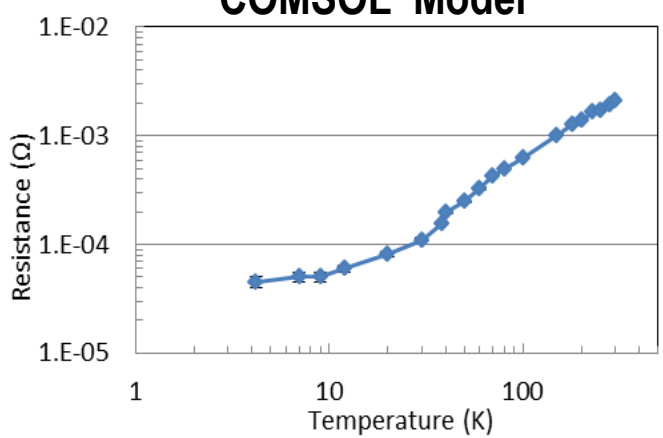
**Independent experiments**




**COMSOL Model**

**Model Output**

transverse resistance




**Matching with experiment**

# Filament-to-matrix contact resistivity

Overview of the filament-to-matrix contact resistivity $R_{\square}$ ($\Omega m^2$):

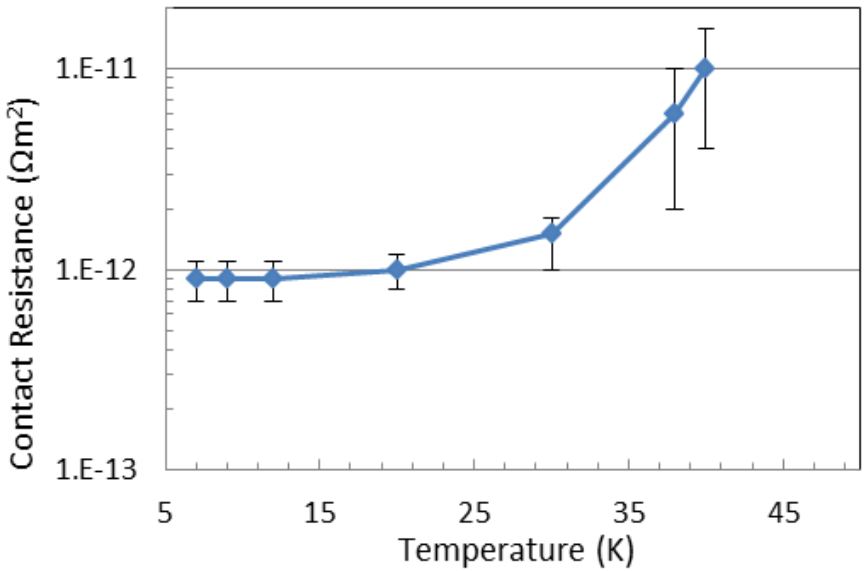
NbTi: ~ $5\times10^{-15}$

$Nb_3Sn$: $1\times10^{-15}$ ~$10^{-14}$

$MgB_2$: ~ $1\text{-}6\times10^{-12}$

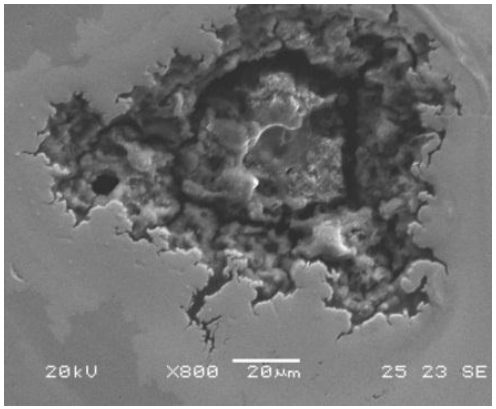
BSCCO: ~ $3\times10^{-14}$ - $2\times10^{-13}$

ReBCO: ~ $1\times10^{-14}$



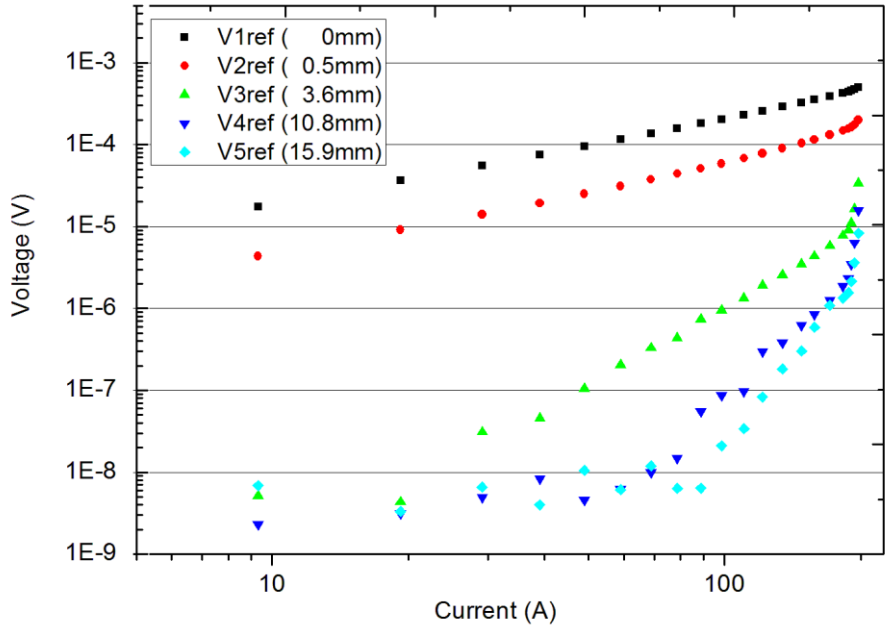

Surprisingly 2 to 3 orders higher than commonly measured (indirect method) for example in NbTi or $Nb_3Sn$ wires.

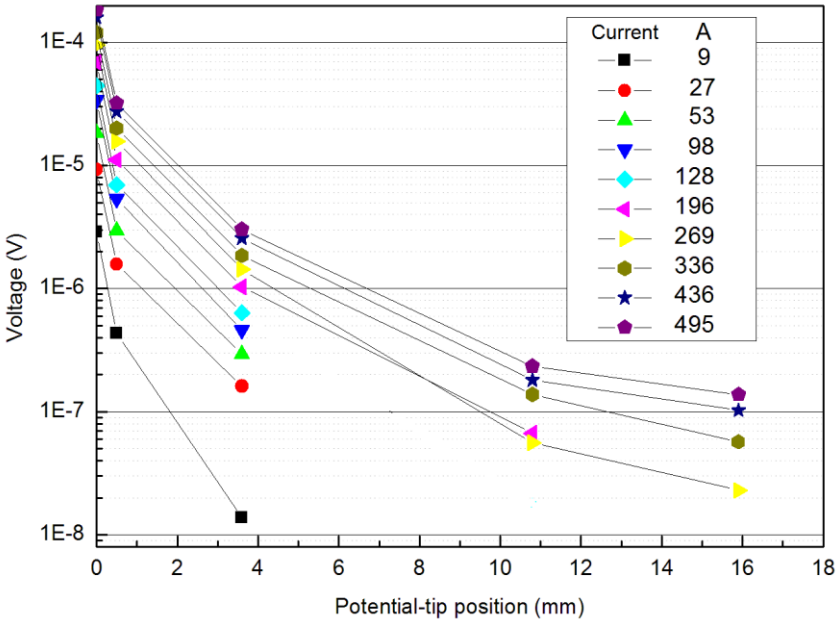
- Inter-metallic layers
- Porosity




C Zhou et al., Supercond. Sci. Technol. 27 (2014) 075002

# Results: current transfer length

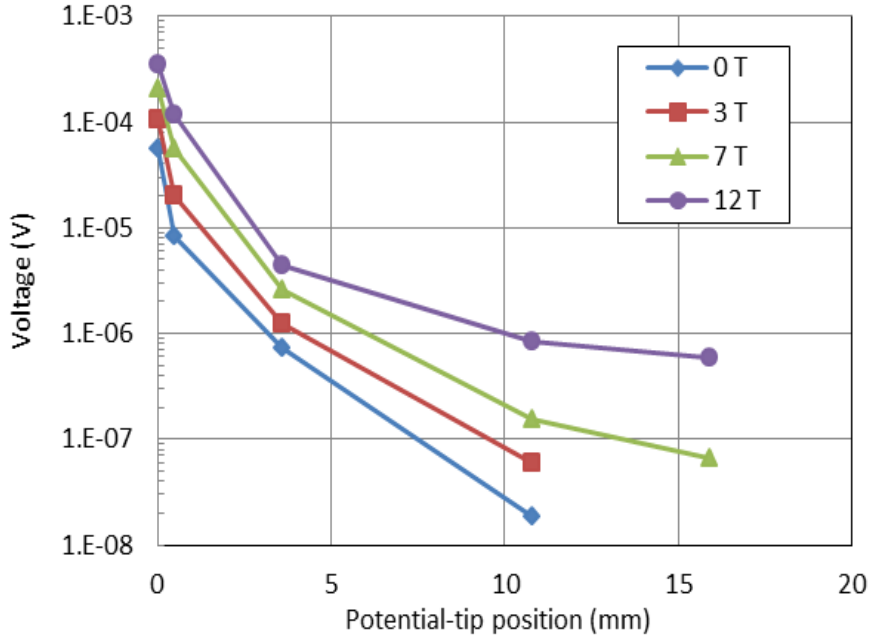


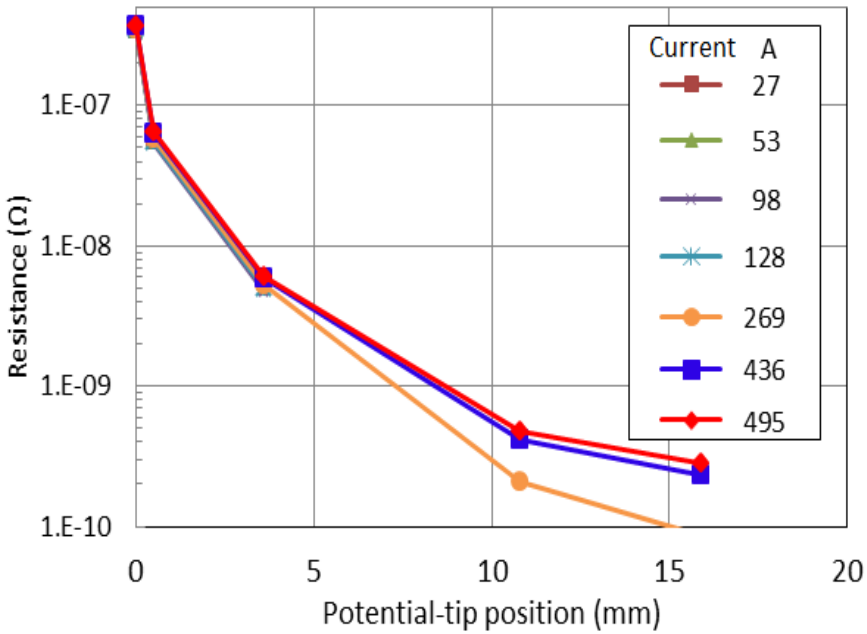




- Experimental results for $Nb_3Sn$ bronze wire with thousands of filaments and high resistive matrix in the filamentary zone

- Note the "classical" current transfer model predicts the current in the matrix to decay exponentially with the distance to the current lead.
- Instead, a distinct upward curvature is noticeable.

# Results: current transfer length

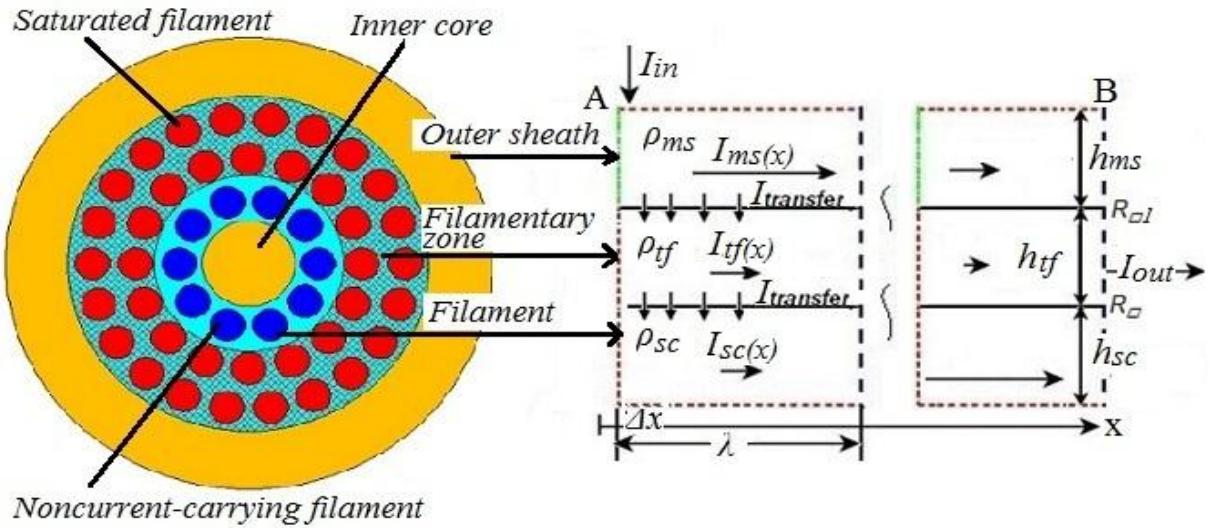



- Dependences of magnetic field and transport current vs. distance away from current joint

- Layer by layer penetration
- Magneto-resistivity

# Model: current transfer length




- A three-layer analytical model is proposed.
- A saturated filamentary ring with increasing thickness along with the injected current is introduced.

$$I_{sc}(x) = I_{in}(1-\exp(-\frac{x}{\lambda}))$$

$$\lambda_{eff} = \sqrt{\frac{R_{\square eff} \cdot h_{ms}}{\rho_{ms}}} = \sqrt{\frac{(R_{\square} + \rho_{tf} h_{tf}) \cdot h_{ms}}{\rho_{ms}}} = \sqrt{\lambda_0^2 + \frac{\rho_{tf} h_{tf} h_{ms}}{\rho_{ms}}}$$

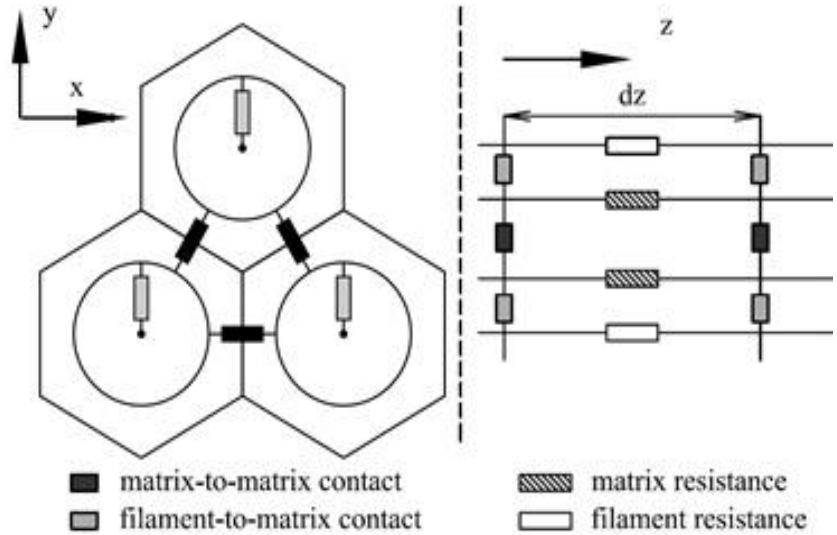
$$\lambda_0 = \sqrt{\frac{R_{\square} \cdot h_{ms}}{\rho_{ms}}}$$

$$R_{\square eff} = R_{\square} + \rho_{tf} h_{tf}$$

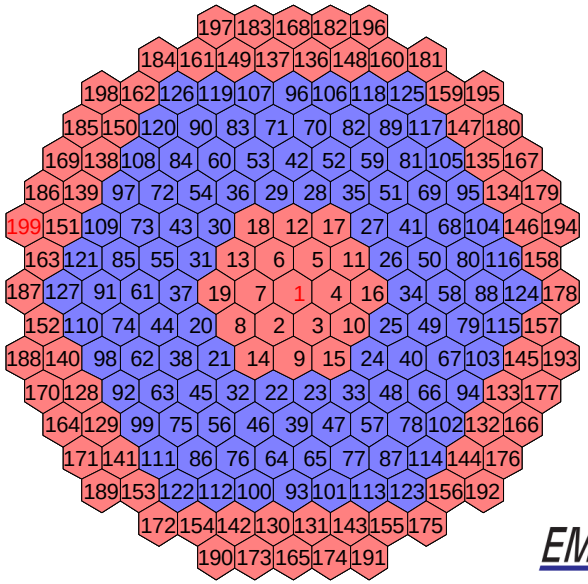
- The effective current transfer length scale $\lambda_{eff}$ adds the influence of the high resistive matrix layer into the 1D 'classical' model.

# 3D Strand Model: current transfer length

- Strand modelled by a 3D resistive network of matrix elements and filaments.
- Filament-to-matrix contact resistance $R_{fm}$ ($\Omega m^2$)
- Transverse coupling resistance between matrix elements.
- Filament resistance is given by power law with $I_c$ and $n$-value

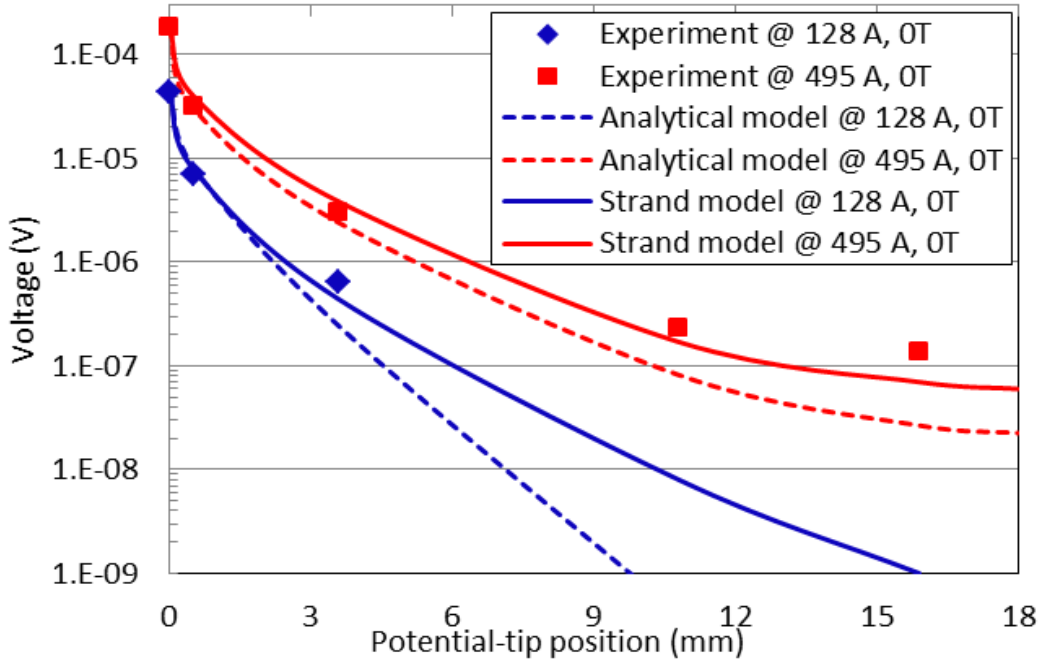



- Input resistive parameters are the measured intra-strand resistances
- Superconducting filament parameters: Ic and n-value
- Boundary condition: the injected current is distributed to the matrix (Cu) in the outer ring.




Y Miyoshi, C Zhou, E P A van Lanen, M Dhalle and A Nijhuis, 'Modelling of current distribution in $Nb_3Sn$ multifilamentary strands subjected to bending', Supercond. Sci. Technol. 25 (2012) 054003

# Results: current transfer length




•A good agreement between strand model prediction and experimental data validates the measured and extracted intra-strand resistance from direct measurements.

•The deviations in the analytical model predictions: increasing with distance, high-likely caused by the difference for the wire shape (a multi-layered block vs circle).

# Summary

- For the first time a systematic study of the intra-wire/tape resistance (direct method) with a wide range of superconductors has been performed.
- The values of filament-to-matrix contact resistivity are mostly in the range of $1\times10^{-15}$ ~$10^{-14}$ $\Omega m^2$, but for $MgB_2$ wire 2 or 3 orders higher is found.
- The extracted parameters give a better insight in the current flow patterns, and allow a quantitative description of the current redistribution process inside strands.
- Extensive database available for further exploration of correlations between strand performance (coupling losses, current transfer length, ...) and strand architecture (materials and layout, crack pattern,…)